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FREQUENCY AND MAGNITUDE OF BEDLOAD TRANSPORT IN A MOUNTAIN RIVER

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ABSTRACT

Magnitude and frequency of bedload transport was examined in the Lainbach River, Bavaria, using magnetically tagged particles. During the study, 18 small to moderate events and one major event occurred. About 1 per cent of the flow period exceeded the entrainment threshold and at least once every year about 50 per cent of the tagged particles were mobile. The major event which occurred during the study period resulted in the deposition of a thick layer of sediment in parts of the channel and passive burial of most of the recovered particles. The step–pool pattern, which characterized the study site prior to the large event, was obliterated. However, the channel recovered quickly and has returned to a new step–pool pattern. The event changed the boundary conditions by increasing the availability of loose sediment and creating higher river-bed slopes in reaches between breached check dams. As a result, movement of individual particles measured for events of both the same magnitude and duration, occurring before and after the large event, yielded different values. For events which occurred after the large event, the range and the mean distance of movement were about ten times higher.

KEY WORDS bedload; magnitude and frequency; tagged particles; mountain river

INTRODUCTION

It is widely accepted that mountain environments experience highly active geomorphological processes (e.g. Caine, 1974; Barsch and Caine, 1984). Relative to lowland streams, gravel-bed mountain rivers are generally highly responsive to process changes, which is explained by the high bedload transport rates. In the case of mountain streams, the recovery and relaxation time associated with extreme inputs of matter and energy are small (Brunsden and Thornes, 1979).

Mountain rivers are often characterized by structures called steps and pools (Whittaker, 1985; Grant *et al.*, 1990); steps are accretions of boulders and gravels. Flow in step–pool systems is described as tumbling flow because it plunges over the steps and forms a hydraulic jump in the pools (Kellerhals, 1972; Peterson and Mohanty, 1960). Local hydraulic jumps and supercritical flow affect bedload transport (Lisle, 1987). As the relative roughness increases, the efficiency and the rate of sediment transport decrease (Mizuyama, 1977; Hassan and Reid, 1990). In addition, the relatively wide range of particle sizes further complicates the sediment transport process. A wide range of sizes may reduce the mobility differences between the large and small particles in the bed (Mizuyama, 1977; Parker and Klingeman, 1982).

The main sources of sediment are from primary erosion of bare rocks, mass wasting and bank and bed erosion, The input of material to the channel is variable and depends on slope stability and flow competence, which leads to a wide range of sediment transport rates for a given flow condition. Ashida *et al.* (1976, 1981)

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noticed that sediment is derived from a limited number of sites within a catchment. Similar results were reported from the Torlesse catchment (Hayward, 1980).

The interaction between sediment transport and channel morphology occurs during infrequent high flows, because of the inherent stability of the step–pool structure (Whittaker, 1987). Most sediment transport occurs during a very short period; Hayward (1980), for example, found that more than 90 per cent of sediment transport occurred in less than 1 per cent of the total flow time. Thus, bedload yield in mountain streams is regulated by both flow conditions and sediment supply. Sediment storage in pools results in complex hystereses in bedload movement (Nanson, 1974; Griffiths, 1980; Whittaker, 1987).

For reasons cited above, considerable difficulties stand in the way of predicting sediment transport in steep streams. However, little attention has been devoted to the study of erosion and sedimentation processes in steep, mountainous gravel-bed streams (e.g. Jackson and Beschta, 1982; Whittaker, 1987). This study examines the hydrological frequency and magnitude of bedload transport in the Lainbach River, an alpine stream in Bavaria (Germany). In this river, bedload was measured in the summers of 1988 to 1992, during which 18 small to moderate events and one major event occurred. Data from transported tagged particles present an opportunity to study the relation between the frequency and magnitude of sediment transport and major channel-forming events.

THE PHYSICAL SETTING AND DATA COLLECTION

The study was conducted in the Lainbach River, Bavaria, approximately 60 km south of Munich (Schmidt and Ergenzinger, 1992). The study site is located downstream of the confluence of two main tributaries of the river, Kotaline and Schmiedlaine (Figure 1). At this point, the 10 m wide channel drains a 15·6 km^2 catchment in the northern parts of the Bavarian Alps. Glacial till, located in the central part of the catchment, is the main source of sediment. The catchment is characterized by relatively unstable slopes; slumps, bank collapses and debris flows are the main sources of sediment to the high mountain tributaries.

Prior to the large flood of June 1990, the 120 m study reach consisted of a step–pool system with side bars. The bed slope averaged 2 per cent in the study reach. The grain size of the bed material ranged between

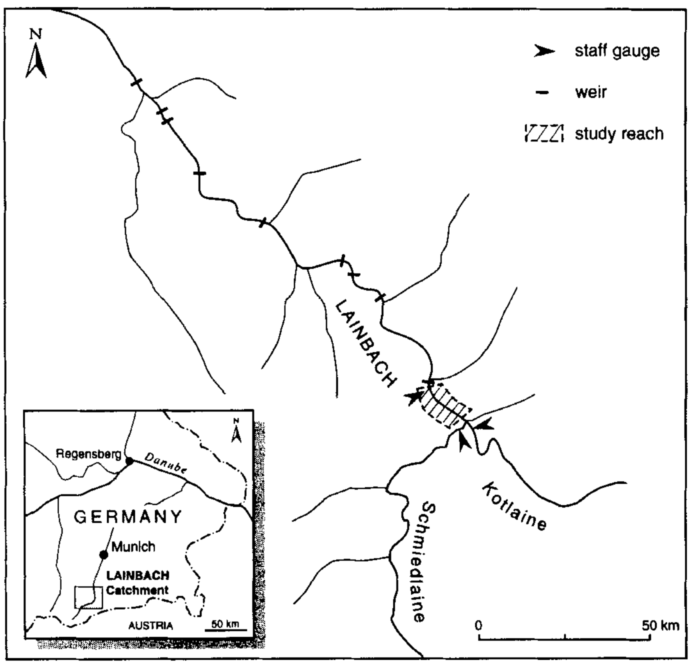

Figure 1. Location map of the Lainbach River

coarse sand, mostly found in the pools and on the lee side of large boulders, to boulders. Boulders larger than 700 mm (*b* axis) covered about 4 per cent of the study reach and formed the steps. They created large roughness elements and remained visible even in moderate flows of about 8 m^3s^{-1} (Stuve, 1990). These elements are relatively stable and move only in extremely high flows. The median size of the bed material varied between bed forms and along the study reach (Ergenzinger, 1992). The median sizes of the bulk bed material (including the surface) taken from two pools were 50 and 65 mm. In the step, the median size ranged between 290 and 800 mm. Cobbles, large pebbles and boulders armoured the thalweg bed surface.

The flood frequency curve based on the annual maximum discharges is shown in Figure 2. The figure is based on records of stream flow over 10 years and can serve only for rough estimates of frequency and magnitude. At the study site, the mean annual maximum discharge is about 30 m^3s^{-1} (Figure 2). Floods occur after snowmelt and heavy rain. The maximum recorded flood, which occurred in the summer of 1990, had an estimated peak discharge (Q_{max}) of 165 m^3s^{-1}. This event changed the bed morphology and slope and created new boundary conditions for sediment transport in the events to follow.

Several generations of artificial magnetically tagged concrete and plastic tracer clasts were used from 1989 onwards. Both types have the same density of 2·65 g cm^{-3} and yielded a similar pattern of behaviour. In a preliminary test, in 1988, 128 iron tracers were used. The number of magnetically tagged particles of each generation ranged between 500 and 1000 particles. The *b* axes of the tagged particles ranged between 30 and 170 mm (mass 100 to 2000 g), covering the range of D_{30}–D_{70} of the bulk material found in bars. The tracers have defined shapes: disc, rod, ellipse and sphere (Sneed and Folk (1958); for more details see Gintz and Schmidt (1991)).

Tagged particles were seeded on the bed surface of pools, steps, bars and stoss side of large boulders (Figure 6). The tracers were placed into their positions by exchanging them with bed surface particles of similar size and shape. After each flow event, the particles were relocated, collected and carried back to the starting positions. The distance of movement was measured and the dispositional environment of each particle was described.

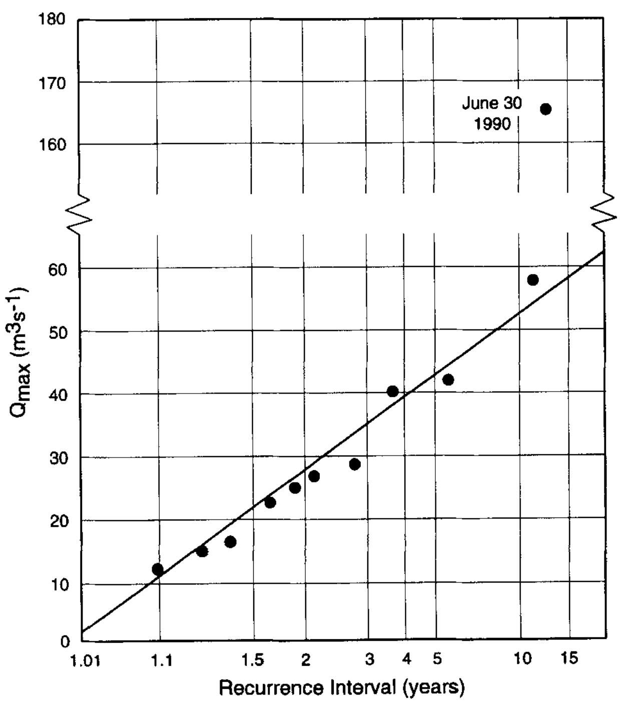

Figure 2. Flood frequency curve of the Lainbach River

Table I. Summary of flow events and sediment movement in Lainbach River

No.	Event	Q_{max} ($m^3 s^{-1}$)	Number of peaks	Flow duration $> 3 m^3 s^{-1}$ (h)	Per cent moved	Mean distance of movement (m) (all particles)	Per cent recovered	Per cent buried	Mean burial depth (cm)	Virtual rate of transport ($m\ h^{-1}$)	Mean distance of movement (m) (moved only)
1	3 August 1988	4·3	1	2·50	46	13	92	3·1	5	6	15
2	13 August 1988	8·9	1	2·75	83	26	80	14·3	6	14	38
3	20 August 1988*	18·5	3	14·00							
4	23 August 1988*	3·2	1	1·00							
5	27 August 1988*	8·5	1	11·00							
6	29 August 1988*	6·3	2	12·50							
7	6 Sept. 1988*	3·4	1	1·00	100	220	23	4·5	6	6	222
8	11–12 July 1989	8·3	2	12·25	42†	41†	95			5	60
9	13–14 July 1989	12·2	1	9·25	52†	63†	93			9	86
10	18 July 1989	3·4	1	0·50	7	0·5	100			14	7
11	28 July 1989	3·9	1	0·75	18	1	100			5	4
12	9 August 1989	3·4	1	2·00	11	1	95			5	9
13	30 June 1990	165	1	52·00	94	115§	25	98	91	2	120§
14	27–28 June 1991	8·7	1	10·50	56	317	80			43	451
15	9 July 1991	3·6	1	1·00	11	8	100			16	16
16	13–14 July 1991‡	19·2	3	66·75							
17	17 July 1991‡	8·25	1	17·00							
18	24–25 July 1991	7·4	1	15·75	65	143	71			14	222
19	22 July 1992	10·2	1	5·75	73	199	88	21	10	47	271

*Cumulative values are given in row 7 for events 3–7
†Tracers on gravel bar are not included
‡Too little time for complete recovery
§Not representative, because only 25 per cent of the tracers were recovered

FLOW EVENTS AND SEDIMENT TRANSPORT

Particle displacement data for individual events are available from 13 events only: one large (30 June 1990) and 12 small and moderate events (1988–1992). Table I presents a summary of the flow events and related sediment movement observations in the Lainbach River. We have data for several events before and after the major event of 30 June 1990, which can be used to characterize the destabilizing impact of the large and extreme event. The events cover a wide range of hydrographs, from simple one-peak events, to multi-peak and long, gradually varied, frontal-precipitation floods. The duration of bedload transport in each event is given in Table I. The threshold discharge needed to entrain and transport the tagged particles is approximately $3\,m^3s^{-1}$ (Busskamp, 1993).

The event of 3 August 1988, the first after the placement of the iron particles, was small and of short duration. About half of the recovered particles moved a short distance and most of them were found on the bed surface, which suggests that no substantial scour occurred in the study reach. The events of 18 July 1989, 28 July 1989, 9 August 1989 and 9 July 1991 were similar in size and flow duration to the 3 August 1988 event. A low percentage of particles moved in the events, and the mean distances of travel were about the same, except for 9 July 1991 event (which occurred after the 30 June 1990 flood) in which the mean distance was about one order of magnitude greater than in other similar events.

The event of 13 August 1988 was approximately twice as large as that of 3 August 1988 (Table I). About 14 per cent of the particles were found buried after the event. Despite the magnitude of the event, the mean burial depth was similar to that obtained for the small event of 3 August 1988. It seems that the bed was stable and the movement was mainly limited to the bed surface. Four events occurred between 20 and 30 August 1988, which made the recovery of the tagged particles after each event impossible. However, one can assume that most of the movement occurred during the dominant event of 20 August 1988.

The event of 11 July 1989 was longer in duration but similar in magnitude to the 13 August 1988 event; however, only 42 per cent of the particles were moved. Twenty-five per cent of the tagged particles were located on a high side bar and the event did not reach them; these particles did not move and they were excluded from the calculations. The mean distance of movement for both events were about the same. Although the 14 July 1989 event was one of the largest events since the study started, the proportion of the moved particles was only about 10 per cent higher than in the 11 July 1989 event. However, the distance of movement was about 30 per cent further than in the previous event.

The event of 30 June 1990 was the largest recorded event during the study period. The event destroyed all of the gauging stations and most of the check dams along the river and the main tributaries. An approximate flow hydrograph was reconstructed using staff gauge measurements and Manning's equation. Details of flow calculation and hydrograph reconstruction are reported in Schmidt (1994). The n in Manning's equation was estimated using average velocity measurement during previous floods, based on surface velocity taken during the flood. These estimates may introduce an estimated error of 20 per cent or more in the discharge. The estimated peak discharge ($165\,m^3s^{-1}$) is about three times higher than the largest previously recorded discharge, which was $58\,m^3s^{-1}$.

Boulders of more than 2 m in diameter were transported by the event from upstream reaches, and destroyed check dams (Schmidt, 1994). Almost all tracer particles were found buried after the event, some by passive burial with no movement, but the majority after a short distance of travel. The burial depth does not reflect the depth of scour by the event but rather reflects its dispositional nature. Despite the magnitude of the event, the mean distance of movement of the relocated tagged particles was less than that of relatively small events, e.g. 27 June 1991 (Table I). This may be due to transport beyond the downstream end of the searched reach (the search covered a reach more than 2 km long) or to burial beyond the sensitivity of the magnetic locator. In addition, a large proportion of the tracers was found buried under a newly formed bar in the upper part of the study reach (see Figure 6b). It seems that the channel at the study site was overloaded by sediment brought from debris flows and upstream tributaries, which explains the limited scour observed and the high proportion of passive burial. Therefore, because of the low recovery rate, data collected during this event were excluded.

Six events were monitored after the large event of 30 June 1990. They were similar in magnitude and

duration to the 1988 and 1989 events. However, the mean distances of movement of the 1991 and 1992 events were about one order of magnitude higher than those of the 1988 and 1989 events.

The duration of flows capable of transporting coarse particles ranged from less than 1 h in small events to more than 50 h for the large and long events (Table I). Based on stream flow records for 10 years, threshold flows were exceeded during about one per cent of the flow duration in each year. Typically, bedload transport events occur a few times each summer (Table I), which is similar to regimes reported for other mountain streams (e.g. Sidle, 1988; O'Connor, 1993).

Figure 3 presents the relation between the percentage of moved particles and peak discharge. The figure also shows the percentage of buried particles for some of the flow events. The threshold discharge needed to initiate the tracers' movement is about $3\,m^3s^{-1}$, which has an estimated recurrence of at least three times per year. A discharge of about $7\,m^3s^{-1}$, with recurrence interval of one year or less, is needed to move about 50 per cent of the tagged particles. On the other hand, a discharge of at least $10\,m^3s^{-1}$ is needed to move most of the tagged particles. Figure 2 shows that such a discharge has a recurrence interval of 1·1 years. The size range of the tagged particles is around median size of the bed material (covering the range of D_{30}–D_{70}), suggesting that about 50 per cent of the bed surface particles are mobile at least once every year. Generally, Figure 3 shows that the sediment mobility increases with discharge.

However, the above estimates are based on values obtained for free and fully exposed particles located on the bed surface. In this study, the mean burial depth of the particles is less than 10 cm and ranges between one and two diameters of the median size. This indicates that a low rate of vertical exchange occurred between the surface and the subsurface material and that most of the movement is concentrated close to or on the bed surface. For example, at a discharge of $10\,m^3s^{-1}$, only one-third of the moved particles were also buried. One should expect a different behaviour for locked and buried particles (e.g. Church and Hassan, 1992).

CHARACTERISTICS OF SEDIMENT TRANSPORT

The distributions of distance of movement of events before and after the extreme event of 30 June 1990 were examined. In our analyses we adopted the method of Hassan *et al.* (1991) and Hassan and Church (1992) but excluded stationary particles (in this case those tracers trapped on the high bar surface). The observed

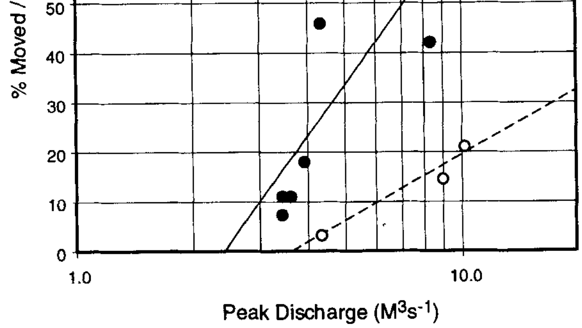

Figure 3. Relation between percentage of moved and buried particles and peak discharge

distances of movement were compared with the two-parameters gamma distribution and the Einstein–Hubbell–Sayre (EHS) model (Einstein 1937; Hubbell and Sayre, 1964; Hassan *et al.*, 1991). The tagged particles were grouped into 0·25 intervals of the mean distance of movement. The gamma distribution was fitted using the maximum likelihood method. Details of the fitting method and the statistical reasoning are found in Hassan *et al.* (1991).

The influence of particle size on the distributions of movement distance was examined. Figure 4a and 4b show the fitted and measured curves for two particle groups (the 2000 g and 500 g particles) for the same event (25 July 1991). The 2000 g particles exhibit a monotonic distribution, while the 500 g particles yield a skew-peaked distribution. Chi-square tests ($\alpha = 0{\cdot}01$) indicate that both the EHS and gamma models fit the data well. However, the differences in the distributions of movement distances between the two size groups are relatively small, and therefore the influence of grain size should not strongly affect the results. We can proceed with the lumped analyses of all sizes in the particle displacements.

Figures 4c–4i show observed and fitted curves of all moved particles. For comparison, the distributions of travel distances for events which occurred before and after 30 June 1990 are presented. Events of about the same magnitude and duration were selected to represent small and moderate events.

The events of 3 August 1988 and 9 August 1989 were small, and were similar in both magnitude and duration (Table I). Most of the particles moved very short distances. Monotonic distributions were obtained for both events (Figures 4c and 4d). In both cases, the chi-square test indicates that the observed data are not satisfactorily described by either of the fitted models.

The event of 9 July 1991 was similar in both magnitude and duration to the events of 3 August 1988 and 9 August 1989. Although the range of distances of movement for the events was about the same, the displacement distributions were different. An asymmetrical distribution (Figure 4e) was obtained for the 9 July 1991 event, which indicates that most of the particles moved about the average distance. However, a chi-square test indicated that the fitted and observed curves are different.

The event of 11 July 1989 was long and consisted of one main peak and a minor one. An asymmetrical distribution of travel distances characterized this moderate event (Figure 4f). An event of similar size occurred on 27 June 1991, and was the first event after the 30 June 1990 event. The range of travel distance obtained for 27 June 1991 was about 10 times larger than that of 11 July 1989. For the 1991 event, the gamma model yielded a monotonic distribution, while an asymmetrical distribution was obtained for the EHS model (Figure 4g). Despite its magnitude, the 30 June 1990 event yielded a downstream displacement distribution similar to those obtained for small events (Figure 4i).

Three events, small, large and medium (Table I), occurred between 27 June and 24 July 1991. The 24 July event was similar in both magnitude and duration to the June 27 event and yielded a similar distribution of travel distances. However, the range of travel distances was much narrower than that of the 27 June event. The shorter distances of movement for the 24 July event indicate that most of the loose sediment had been evacuated, and that initial rearrangement and armouring of the surface sediment had begun. This is also indicated by the formation of a riffle–pool pattern and the re-establishment of the characteristics of the former longitudinal profile (see Figure 7).

Generally, the data are highly skewed, especially those of the 1991 events, and are usually peaked. The distributions tend to be irregular, with secondary modes in all presented results including those of the 2000 g and 500 g stones. In addition, the data are very noisy, even though the 1991 events are based on relatively large numbers of particles (about 400). The secondary modes probably demonstrate the downstream effect of sedimentation traps, such as bars and pools, on the longitudinal displacement of sediment. These effects are particularly obvious when the tracers were transported over distances in excess of 100 m.

Hassan *et al.* (1992) suggested empirical relations between the mean distance of movement and the virtual rate of travel, and the excess stream power. These relations are based primarily on data collected from rivers with well developed riffle–pool systems. In order to examine the validity of such relations in the Lainbach data, we enquired into the relation between mean distance of movement and excess stream power. The threshold power needed to initiate movement of the tagged particles was measured in the field using radio tracers (Busskamp, 1993). The choice is a matter of convenience; errors associated with estimating the critical power needed to entrain the tagged particles in steep step–pool channels (for further discussion see

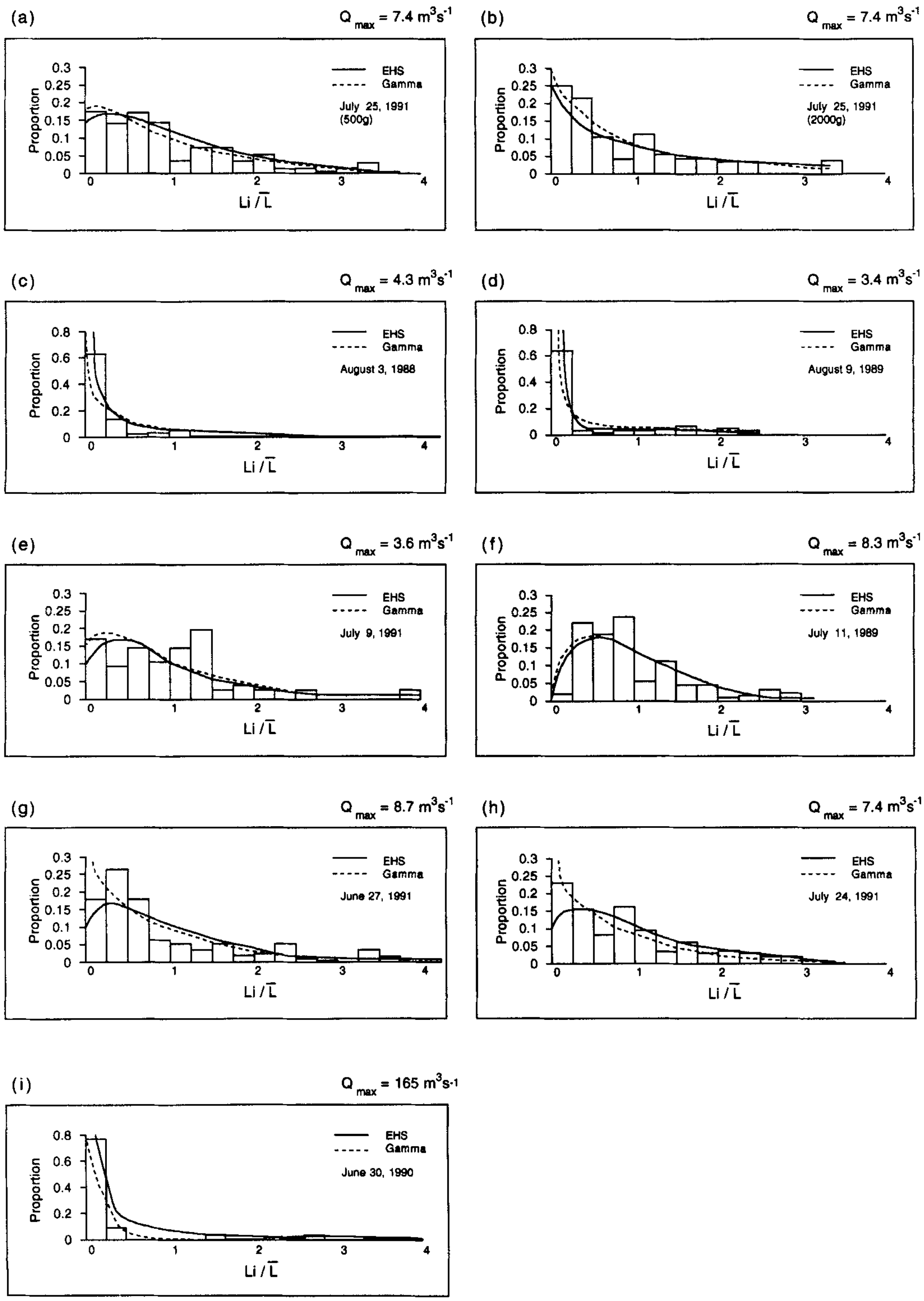

Figure 4. Downstream displacement of moved tagged particles: field data and fitted gamma and Einstein–Hubbell–Sayre models. Data were grouped within intervals equal to 0·25 of the mean travel distance for the examinated event. Li = distance of movement; $\bar{L}$ = mean distance of movement

Ferguson (1994)) are significantly reduced by using the radio tracers. In the analysis we followed the method recommended by Hassan *et al.* (1992). The relation between the mean distance of movement and the excess stream power is presented in Figure 5A. In addition to the Lainbach data, the average relation obtained for riffle–pool rivers is plotted (from Hassan *et al.*, 1992, Figure 1B), for comparison. The best-fit line is slightly steeper than that of the riffle–pool relation. However, the overall body of data is relatively well represented by the riffle–pool average relation. The scatter of the Lainbach data is comparable with that obtained in other studies of fluvial sediment transport (e.g. Hassan *et al.*, 1992).

Figure 5B shows the relation between the virtual rate of travel and the excess stream power for the Lainbach data. Small events yielded values higher than those obtained from the riffle–pool relation, while the

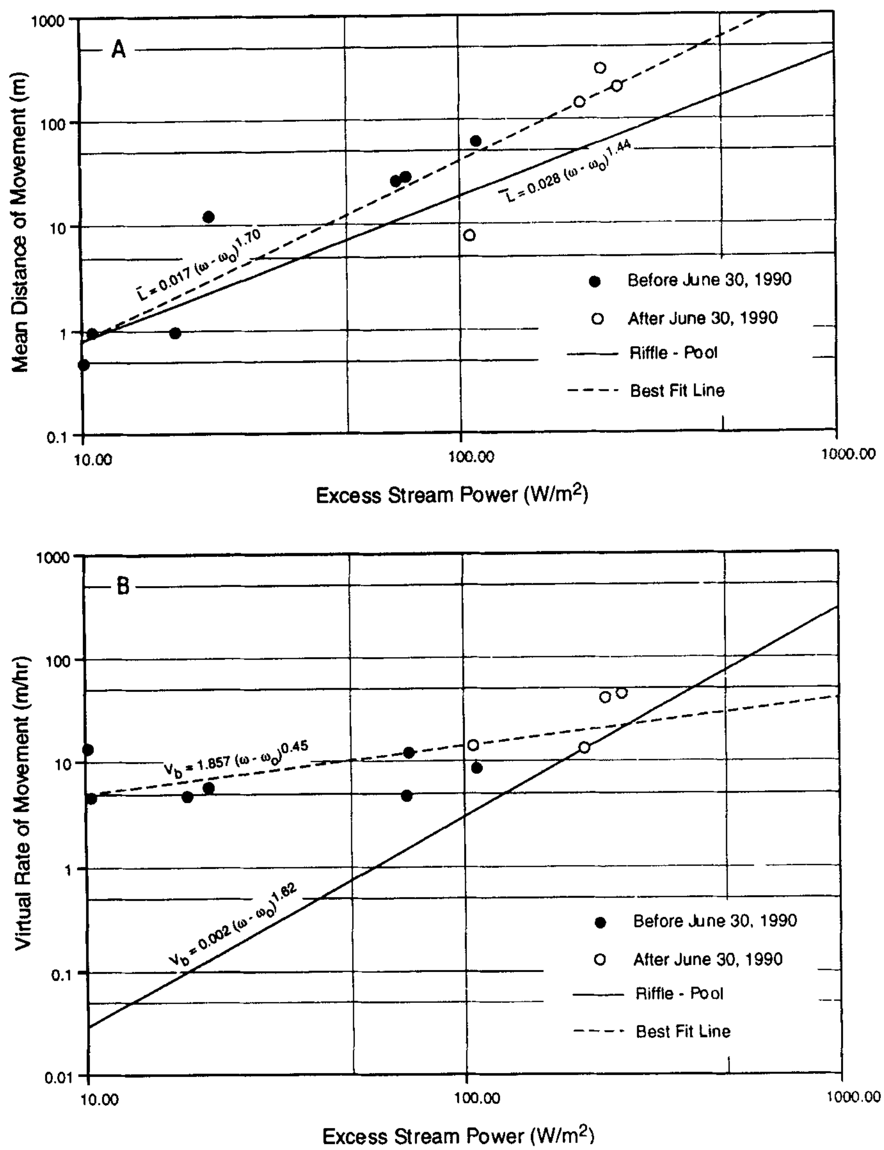

Figure 5. (A) Relation between mean distance of movement and excess stream power as calculated for the peak discharge. (B) Relation between virtual rate of travel and excess stream power as calculated for the peak discharge. Solid lines represent the average relation obtained for riffle–pool rivers (after Hassan *et al.*, 1992). The critical stream power was estimated using radio-tracer data. ω = excess stream power, ω_0 = critical stream power, $\bar{L}$ = mean distance of movement, V_b = virtual rate of movement

data obtained from large events plot close to the riffle–pool average relation. The relatively high values obtained for the small events may be due to the fact that the tagged particles were located on the bed surface.

BED MORPHOLOGY AND THE IMPACT OF THE 30 JUNE 1990 EVENT

The 30 June 1990 event was triggered by heavy and continuous rain. During the event, most of the tributaries contributed sediment to the main channel. The riverbeds of the Kotlaine (Figure 1) and the Lainbach were surveyed after the flood. In comparison with the pre-flood survey, a net sedimentation of 27 000 m^3 occurred in the Kotlaine. In the mountainous part of the Lainbach another 8000 m^3 of net accumulation was observed. Field inspection showed that most of the sediment originated from destroyed check dams located upstream of the study reach (Schmidt, 1994).

In contrast with the Kotlaine basin, 22 valley-side slumps and two debris flows occurred into the Schmiedlaine main channel. The two debris flows occurred after the peak discharge (De Jong, 1992). Approximately 5500 m^3 of material was deposited in the lower reach of the Schmiedlaine, immediately upstream of the Lainbach confluence.

The event deposited sediment in most segments of the study reach. A significant number of the tracers were found buried *in situ* with little or no movement. The burial depth ranged between zero (exposed particles) and 1·4 m. Most of the recovered particles were found in bars and pools.

Changes in the bed morphology are presented in Figure 6. The 1989 map shows a well developed step–pool pattern in a single channel with relatively high side bars (e.g. stations 0–45 m, Figure 6a). The 30 June 1990 event resulted in the destruction of the step–pool pattern and the creation of three new bars: the first (A in Figure 6b) in the upper 20 m on the left side of the study reach, the second (B in Figure 6b) in the upper 30 m on the right side of the study reach, and the third (C in Figure 6b) in mid-channel between stations 80 and 110. In fact, the step–pool pattern became buried under the newly deposited material. In terms of sediment texture, the median size of the bed material rose from 96 mm before the event to 125 mm after the 1991 events. This coarsening reflects winnowing and reworking of the flood deposit, rather than its initial condition. By the end of 1992, a pattern of bed morphology similar to that of 1989 was evident. It seems that events occurring after 30 June 1990 managed to destroy the new bars and to re-establish a pattern of step–pool and side bar morphology (Figure 6c).

The changes in the bed morphology should be reflected in the longitudinal profiles. The stepped pattern observed in 1988 is replaced by a relatively steep but continuous slope by the end of 1990 (Figure 7). However, Figure 7 shows that most of the changes occurred in the upper part of the study reach (stations 0–25). The average slope in the study reach increased from 2 per cent in 1988 to 3·5 per cent in 1990. Events occurring after June 1990 scoured most of the deposited material. The result is that between stations 0 and 60, the river recovered its 1988 profile. In addition, headward erosion from a check dam below the study reach resulted in a steeper profile.

SUMMARY AND DISCUSSION

Sediment transport in high mountain streams depends on flow competence and sediment supply to, and availabilities in, the channel. The deposition of the solid load defines channel morphology, which is altered by entrainment, transport and deposition during relatively high discharges. Sediment transport and channel morphology both reflect bed and bank shear stress and sediment supply from the adjacent slopes.

The tagged particles, which ranged in size between the D_{30} and the D_{70} of the bed material, were typically entrained at a discharge of approximately $m^3 s^{-1}$. Over the study period, this entrainment threshold was exceeded approximately 1 per cent of the time. Bedload movement was sporadic and occurred only a few times each year. However, at least once every year, 50 per cent or more of the tagged particles were mobile.

The impact of the 30 June 1990 event on bed morphology and sediment movement demonstrates the relative importance of sediment supply. The event was exceptional because of the high input of sediment from upstream tributaries, and the destruction of check dams. Despite its high magnitude, the event resulted in the

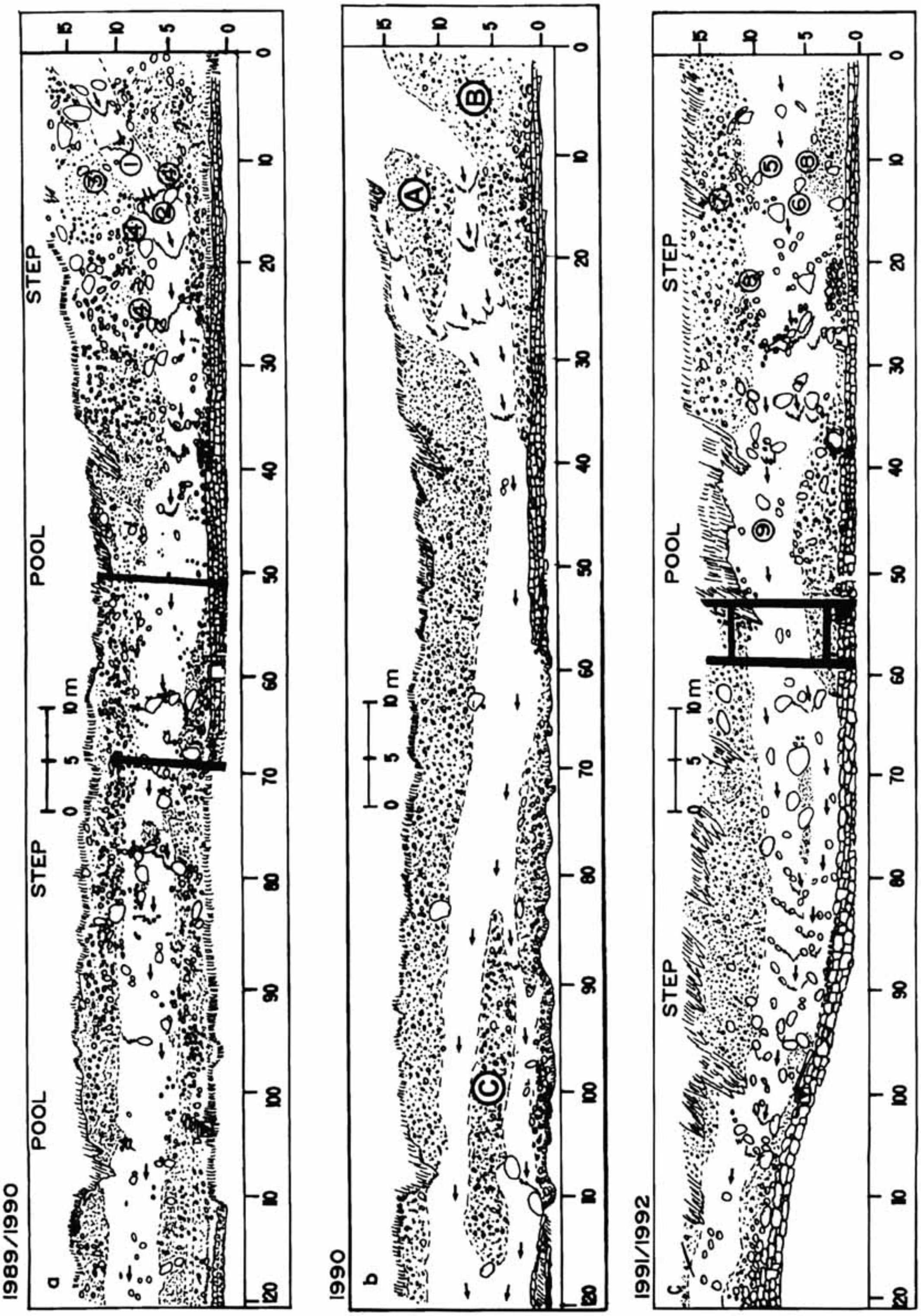

Figure 6. Bed maps showing changes in the channel morphology before and after the 30 June 1990 event: (a) 1989; (b) after 30 June 1990 event; (c) 1992. Numbers refer to locations of the tagged particles and letters indicate the newly formed gravel bars

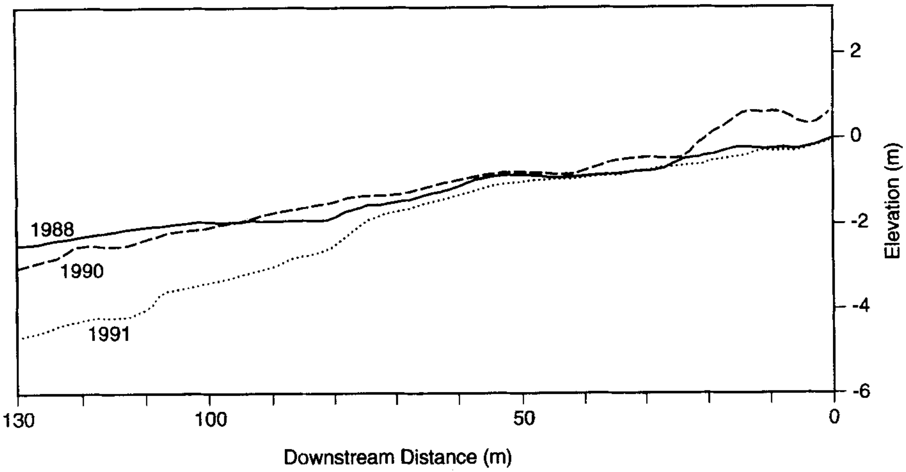

Figure 7. Changes in the longitudinal profiles of the upper part of the study reach over the study period. Elevations refer to local datum

deposition of a relatively thick layer in the study reach. A significant proportion of the tagged sediment moved short distances and was found buried after the event, which is reflected by the mean distance of movement and burial depth of the particles. It seems that the large input of sediment to the study reach consumed most of the available excess power and significantly limited local erosion. A similar result from desert streams was reported by Hassan (1993).

Prior to the 30 June 1990 event, a well developed step–pool pattern characterized the study site. This architecture was buried by the event but the channel recovered quickly, and within two years a new step–pool pattern was established. This might be due to the relatively loose nature and fine calibre of the material deposited by the event, which facilitates reworking by subsequent events.

The overall relation between the mean distance of movement and excess stream power tends to vary around the average relation obtained for riffle–pool rivers. Although the peak discharges were similar, events which occurred after the 30 June 1990 event yielded larger mean distances of movement than those which occurred before the event. The large event of 30 June 1990 demonstrates the importance of sediment supply for the behaviour of mountain rivers. Furthermore, the response of the local study reach to such an extreme event emphasizes the need to integrate the availability of sediment to frequency and magnitude analyses. In addition, comparison between events prior to and after 30 June 1990 demonstrates the influence of bed structure and morphology on sediment entrainment and transport. The loose sediment which was deposited by the extreme event resulted in changing bed conditions and increased the mean travel distances of the particles relative to similar events which occurred during 1988 and 1989.

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